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# Microgravity Combustion Science: A Program Overview

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# MICROGRAVITY COMBUSTION SCIENCE: A PROGRAM OVERVIEW

*"Microgravity science research has not had a long history of space experimentation but is now emerging as a potential major user of space for science..."*

*—The Crisis in Space and Earth Science*

*"There are two related reasons for interest in microgravity from the most fundamental scientific point of view. The more mundane is that gravity often induces effects that obscure essential features of the phenomena being studied...The second, more dramatic reason...is the real possibility of discovering completely new phenomena."*

*—Space Science in the 21st Century*

## Introduction

The study of fundamental combustion processes in a microgravity environment is a relatively new scientific endeavor. A few simple, precursor experiments were conducted in the early 1970's. Today, the advent of the U.S. space shuttle and the anticipation of Space Station Freedom provide for scientists and engineers a special opportunity—in the form of long duration microgravity laboratories—and need—in the form of spacecraft fire safety and a variety of terrestrial applications—to pursue fresh insight into the basic physics of combustion.

The microgravity environment enables a new range of experiments to be performed since:

- *Buoyancy-induced flows are nearly eliminated.* Because of the hot, less dense reaction products of combustion, buoyancy-induced flows tend to develop in normal-gravity experiments, promoting self-turbulization, instabilities, and even flame extinction. Microgravity reduces these flows and their attendant complications. Furthering our understanding of low-gravity behavior can, by direct comparison, further our understanding of normal-gravity combustion processes.
- *Normally obscured forces and flows may be isolated.* Buoyancy frequently obscures weaker forces, such as electrostatic, thermocapillary, and diffusional forces, which may be particularly important near flammability limits. Further, low-velocity forced flows can not normally be studied because of the onset of mixed convection. By removing buoyancy, the roles of these forces and flows may be observed and compared with theory.
- *Gravitational settling or sedimentation is nearly eliminated.* Analogous to containerless processing of materials, unconstrained suspensions of fuel droplets or particles may be created and sustained in a quiescent environment, eliminating the need for mechanical supports, levitators, or stirring devices and enabling a high degree of symmetry.
- *Larger time or length scales in experiments become permissible.* To limit buoyancy effects in normal-gravity experi-

ments, the size or duration of tests is often constrained. Microgravity permits larger scale experiments which, in turn, allow more detailed diagnostic probing and observation.

The range of experiments completed to date has not been broad but is growing. As will be discussed, unexpected phenomena have been observed often in microgravity combustion experiments, raising questions about the accuracy and completeness of our classical understanding and our ability to estimate spacecraft fire hazards. Because of the field's relative immaturity, instrumentation has been restricted primarily to high-speed photography. More sophisticated diagnostic instrumentation—similar to that evolving in terrestrial laboratories—is being developed for use on Space Station Freedom and, along the way, existing microgravity facilities.

The purpose of this document is to provide an introduction to the promise of microgravity research by way of a brief survey of results, the available set of reduced-gravity test facilities, and plans for experimental capabilities in the space station era.

The following people, listed alphabetically, contributed to the writing of this report: Robert Friedman, Paul Greenberg, John Haggard, Jack Lekan, Sandra Olson, Howard Ross, Kurt Sacksteder, and Dennis Stocker.

## Microgravity Facilities

As shown in figure 1, several facilities provide a free-fall or semi-free-fall condition where the force of gravity is unopposed, thus enabling a low-gravity environment for scientific studies. Each facility's capabilities and characteristics must be considered by an investigator in choosing the facility best suited to a particular series of experiments.

To date, most combustion studies have taken place in the NASA Lewis Research Center's two drop towers and its model 25 Learjet. The 2.2-Second Drop Tower, as its name implies, provides 2.2 sec of low-gravity test time for experiment packages with up to 125 kg of hardware mass. A schematic

diagram of this drop tower is shown in figure 2(a). Within this building is the drop area, which is 27 m tall with a cross section of 1.5 by 2.75 m. The experiment package, an example of which is shown in figure 2(b), is enclosed in a drag shield

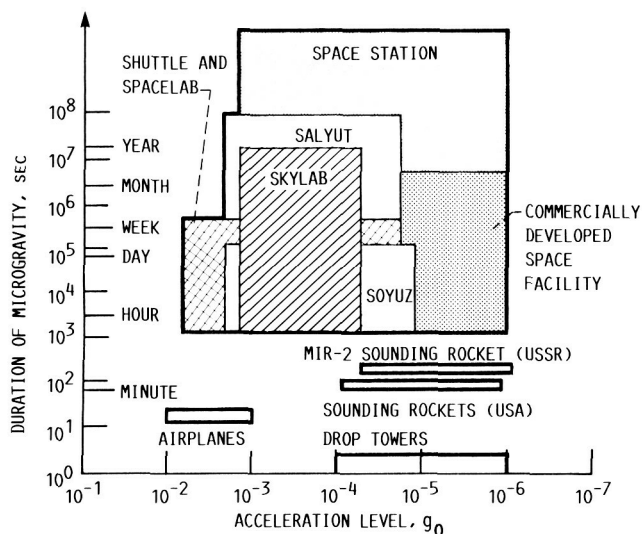
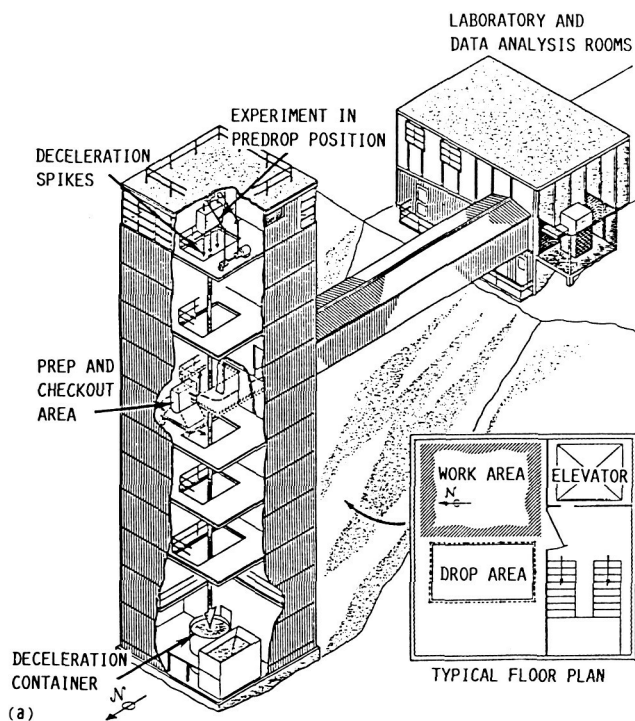


Figure 1.—Characteristic times and acceleration levels of microgravity laboratory facilities.

that has a high ratio of mass to frontal area and low drag coefficient. The drag shield and experiment assembly are hoisted to the top of the building and suspended there by a highly stressed music wire, which is attached to the release system. A drop begins when a pneumatic system notches the wire causing it to fail. As the drag shield falls, the experiment package is free to move within the drag shield. The only external force acting on the freely falling package is the air drag associated with the relative motion of the package within the drag shield. Although the low-gravity time is only 2.2 sec, this facility offers both low cost and rapid turnaround time between experiments. It is often used for proof-of-concept or precursor experimentation.

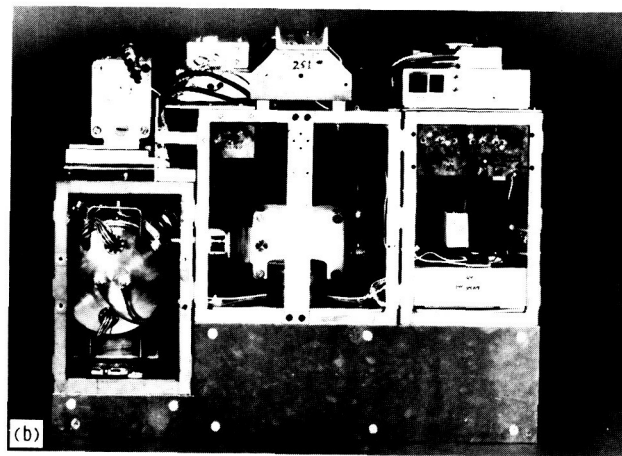
The 5.18-second Zero-Gravity Facility at Lewis, with its 132-m free-fall distance in an evacuated drop chamber represents a significant expansion in experiment sophistication and research capabilities over the 2.2-Second Drop Tower. A schematic of this facility is shown in figure 3(a). The Zero-Gravity Facility houses a 6.1-m-diameter steel-walled vacuum chamber that is 145 m deep. The drop distance of 132 m provides 5.18 sec of free fall and accelerations of about  $10^{-6}g$ . Experiments of up to 450 kg are mounted in a 1-m-diameter drop bus (fig. 3(b)). The entire chamber is then evacuated to  $10^{-2}$  torr. The drop begins when a bolt in the release mechanism is sheared. The bus falls free of drag in the near vacuum and is decelerated in a 6.1-m-deep container of small pellets of expanded polystyrene. Data can be

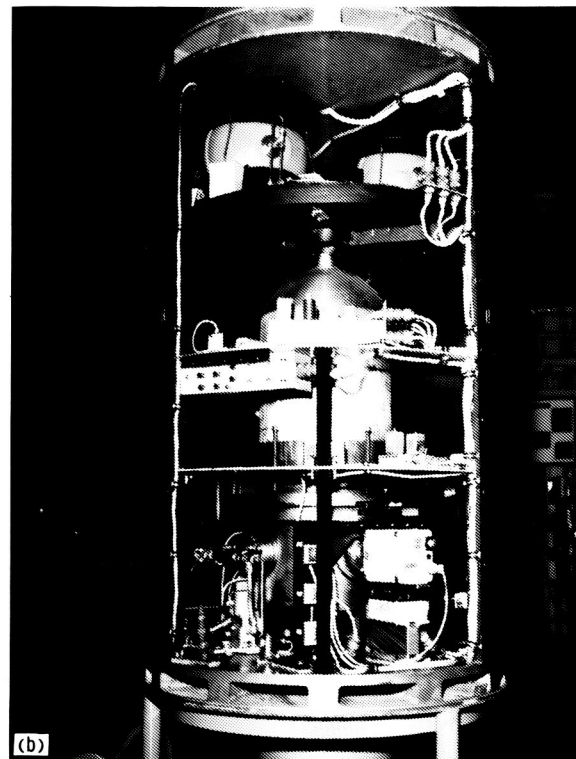
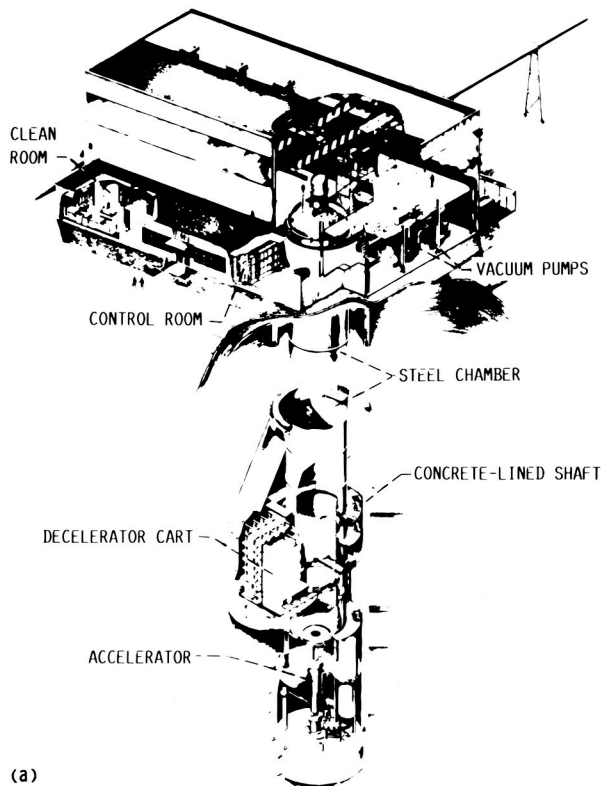


(a) Facility.

(b) Experiment package (droplet combustion experiment).

Figure 2.—The NASA Lewis 2.2-Second Drop Tower.





(a) Facility.  
(b) Experiment vehicle (combustion chamber).  
Figure 3.—The NASA Lewis Zero-Gravity Facility.

transmitted via telemetry during the drop, allowing the researchers to monitor the progress of the experiment in real time.

Specially modified jet aircraft flying parabolic (Keplerian) trajectories can provide longer low-gravity experiment times than drop towers, but not without the penalty of higher gravity levels. For an experiment fixed to the body of an aircraft, accelerations in the range of  $10^{-2}g$  can be obtained for up to 20 sec. During one flight, several trajectories are possible. While aircraft may not offer true microgravity, they do offer the significant advantage of permitting researchers not only to monitor their experiments in real time, but also to reconfigure them between trajectories. The Lewis airborne low-gravity facility, a Learjet model 25, is shown in figure 4 along with a flight profile of a low-gravity trajectory. Approximately 1.8 m of cabin length is available for experiment mounting and researcher seating. Inherent engine lubrication limitations of this aircraft permit a maximum of six trajectories per flight. Intermediate acceleration levels of  $1/20$ ,  $1/10$ ,  $1/6$  (lunar gravity),  $1/5$ ,  $1/4$ ,  $1/3$  (Martian gravity),  $1/2$ , and  $3/4$  of Earth's gravity can be achieved in this aircraft.

The Johnson Space Center's KC-135 aircraft operates in a similar fashion to the Learjet when flying experiments fixed to the aircraft body, but, because of its size, also permits free-floated experiments with acceleration levels of about  $10^{-3}g$

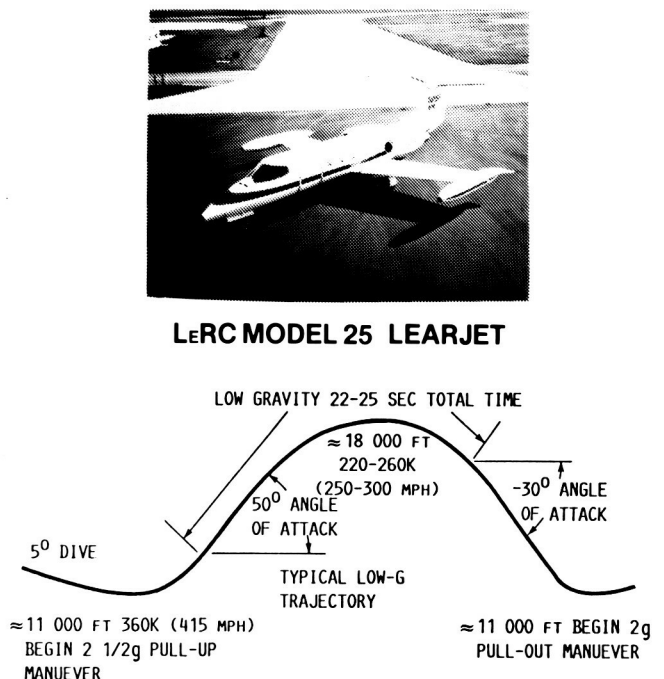


Figure 4.—Lewis airborne low-gravity facility.



for 5 to 15 sec. Also, up to 40 trajectories can be performed in a single flight. The European Space Agency has performed combustion experiments in this facility, and U.S. combustion studies using this aircraft are underway.

Although they have not yet been used by the U.S. microgravity combustion program, sounding rockets can provide a low-gravity environment of  $10^{-4}g$  for about 300 sec. Their use will be considered in the future for experiments that require a compatible time and gravity level but do not require direct observation by a researcher.

Truly long-duration microgravity combustion experiments require space-based laboratories such as the U.S. space shuttle or Space Station Freedom. The shuttle flight duration for science missions is typically 7 to 10 days. The combined aerodynamic and gravity gradient forces provide a background acceleration level of around  $10^{-6}g$ . Crew motion, the most significant disturbance, can induce accelerations in the range of  $10^{-3}g$ . Many investigators, therefore, request that their experiments be operated during periods of reduced crew activity when low-gravity conditions on the order of  $10^{-4}g$  can be sustained. Upward and downward data communication links are available over the Ku-band. Thermal control, physical space availability, and electrical power capability depend on where an experiment is mounted in the shuttle (e.g., middeck locker or cargo bay) or on the type of mission (e.g., Spacelab). Substantial astronaut involvement is not only possible but encouraged for middeck or Spacelab experiments.

In the future, Space Station Freedom will provide the highest quality, longest duration low gravity (see again fig. 1). Within its instrument racks will be dedicated space, electrical power, and advanced diagnostic instrumentation for microgravity combustion experiments. Multiuser experiments will be conducted in experiment modules by scientific specialists. Principal investigators on Earth will have the capability of monitoring and modifying in real-time the performance of their experiments. This future facility, along with the means by which investigators' experiments will be selected for flight, are discussed later in this document.

## Microgravity Combustion Experiments

In the following sections a sampling of microgravity combustion experiments is provided. All of the findings have been accomplished to date in drop towers or aircraft. However, the sequential development of single-user, multiuser, then facility-class flight hardware is underway to take advantage of the expanding space-based capabilities for combustion research.

### Solid Materials Flammability

The combustion of solid materials in low-gravity environments is a key area of research not only for improving our fundamental understanding of the mechanisms of solids

combustion, but also for improving the fire safety of human spaceflight.

Many processes contribute to the propagation of a flame over a solid fuel. Conduction, convection, and radiation of heat from the flame all determine the balance of the heat produced within the flame and of the heat lost to the environment and used in vaporizing the solid fuel. Both surface pyrolysis of the fuel and gas-phase chemical reactions are vital processes in the production of heat needed to sustain the flame. Species diffusion and convection must also occur so that the appropriate mixture of fuel and oxidizer are present within the reaction zone to allow the reaction to proceed. Additionally, the products of reaction must be removed so that they do not extinguish the flame. With all of these interacting processes involved in flame spread, it is difficult to determine which process is dominant. By eliminating gravitationally induced buoyant flows and the associated heat and mass transport, other transport processes can be studied directly.

Figure 5 illustrates the importance of gravity on the burning of a solid fuel. A flame is shown spreading over a thin solid fuel. Three flow environments are drawn upstream of the spreading flame. In low gravity the flame encounters fresh oxidizer as it spreads across the solid. Thus, the flow environment influencing the flame is simply a uniform flow at the flame spread rate (fig. 5(a)). If a forced flow opposes the flame spread, a boundary-layer type flow is superimposed on the spread rate (fig. 5(b)). In normal gravity the large temperature gradients across the flame cause large density

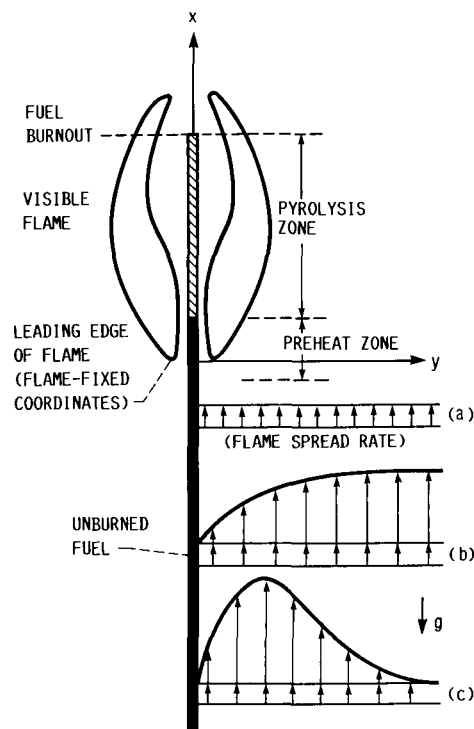


Figure 5.—Schematic of three velocity profiles seen by the flame in opposed-flow spread over a thin solid fuel.

gradients in the gas phase, which induce a buoyant flow of gas to oppose the flame as it propagates down a solid material. This buoyant flow is depicted in figure 5(c) superimposed on the flame spread rate.

Recent experiments have focused on the importance of gas-phase flow in the flame spread process. A variety of fuels have been studied; these fuels range in thickness from very thin paper samples to thick slabs of plastic. Results to date have been obtained in terrestrial low-gravity facilities; however, a shuttle experiment entitled "Solid Surface Combustion Experiment" (SSCE) is scheduled to fly on the USML-1 Spacelab mission in 1992.

The flight hardware for SSCE is shown in figure 6. During its first flight, an ashless filter paper fuel sample will be burned in a quiescent, low-gravity environment to determine the effects of gravity, oxygen concentration, and pressure on the burning process. Flame spread will be captured on color motion-picture film, and flame and pyrolysis temperatures and pressure rise in the chamber will be recorded for later analysis. Eight flights in all are planned for this experiment, which will study both paper and plastic fuels in quiescent, low-gravity environments.

Drop-tower experiments with very thin paper samples have revealed a strong effect of very low-velocity flows on the flame spread process. Figure 7 shows three flames spreading over paper samples in varying convective environments. Figure 7(a) is a microgravity flame spreading in a quiescent air environment. It is very weak and cool, as indicated by its diffuse blue color. If a very slow velocity flow opposes the flame spread, as in figure 7(b), the resulting air flame is greatly strengthened; the flame's blue color is more intense; soot forms within the flame zone; and the flame moves closer to and spreads more rapidly along the fuel surface. The normal-gravity counterpart flame in a higher velocity, buoyancy-induced opposing flow is shown in figure 7(c). Here, the flame is very close to the fuel surface and produces a great deal of soot within the flame zone, which is indicative of a hot flame. It spreads correspondingly faster over the fuel surface.

Figure 8, a flammability map for paper, indicates the oxygen atmospheres and flow environments where the material will burn. Two flame extinction processes have been found. Each makes up a separate branch of the extinction curve. At high opposed-flow velocities, blowoff extinction is caused by long reaction times compared with the short residence time of gas

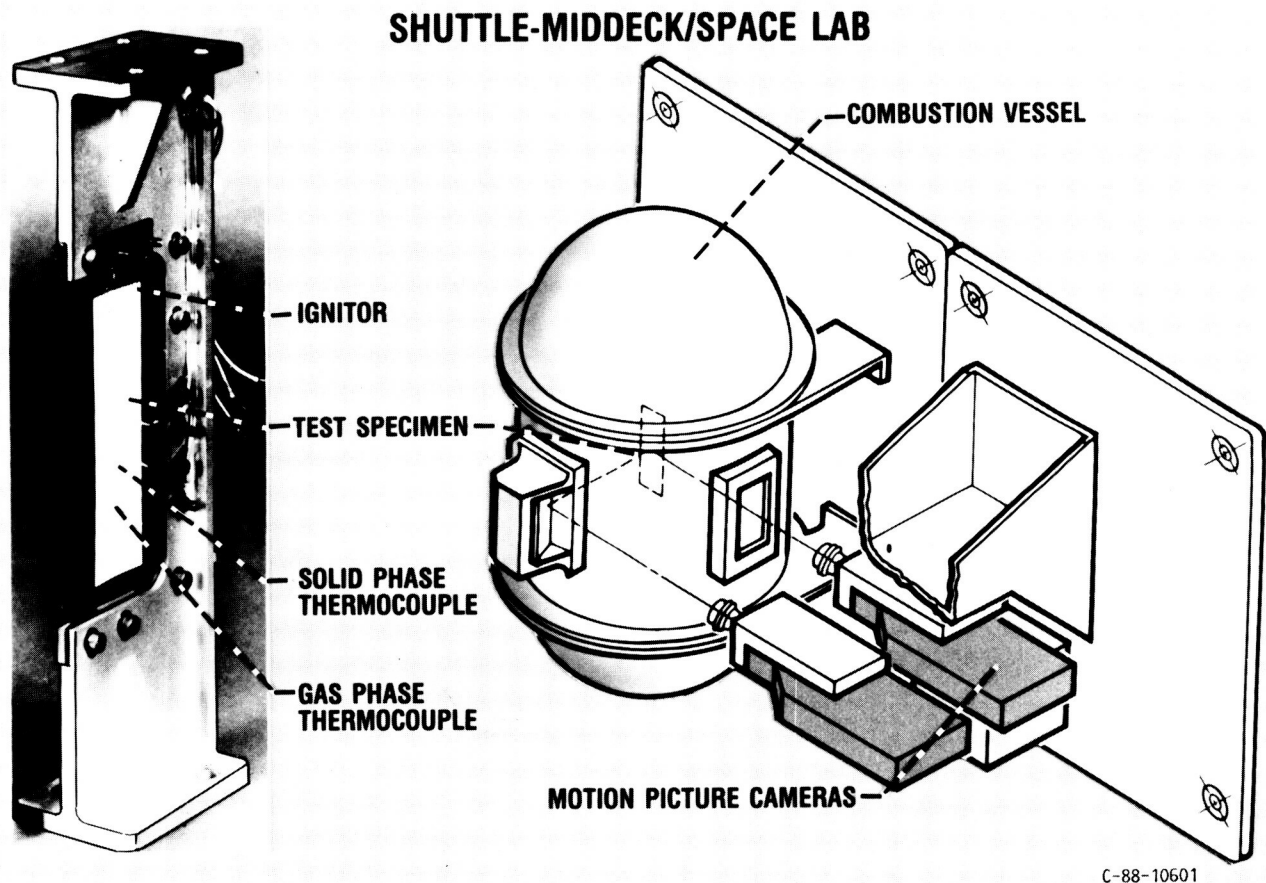
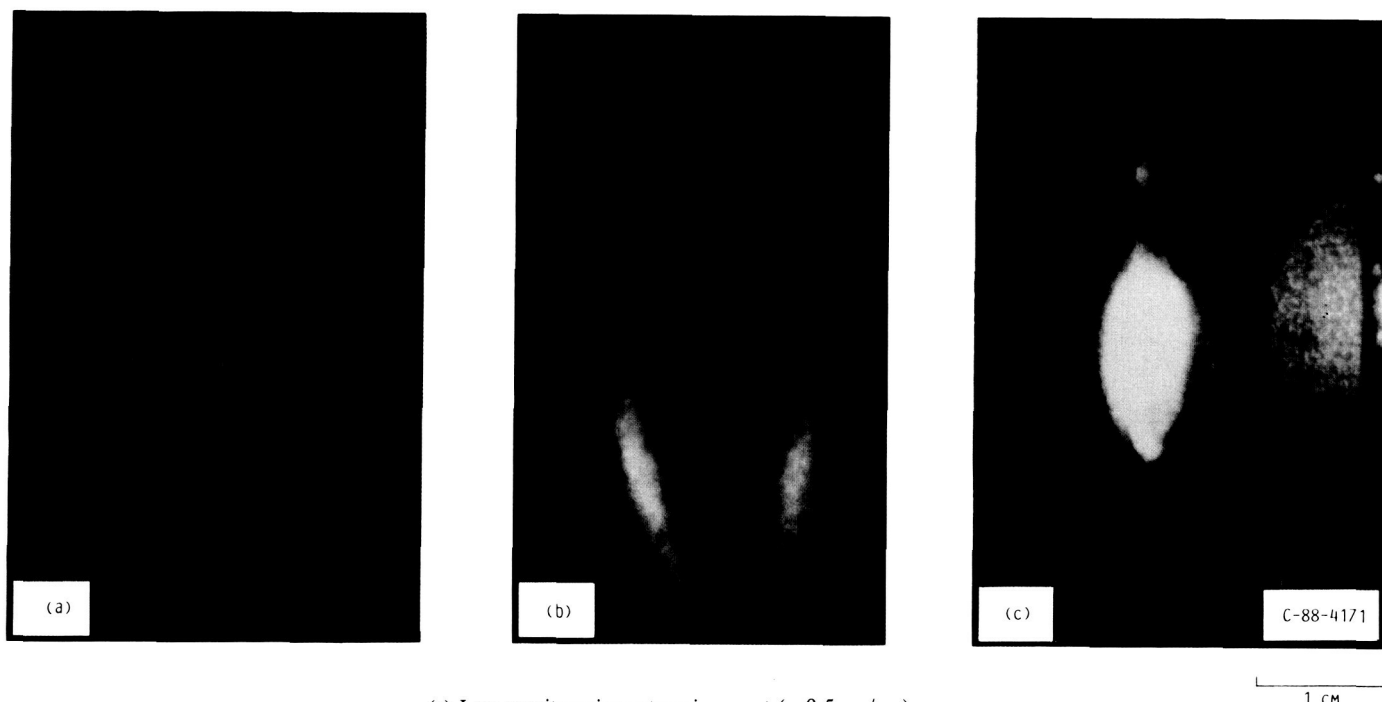


Figure 6.—Shuttle flight hardware for the solid surface combustion experiment, which is scheduled to fly in 1992 on Spacelab 1.



(a) Low-gravity quiescent environment ( $\sim 0.5$  cm/sec).  
 (b) Low-gravity slow convection environment ( $\sim 7$  cm/sec).  
 (c) Normal-gravity buoyant environment ( $\sim 90$  cm/sec).

Figure 7.—Three flames spreading over paper in air, in different convective environments

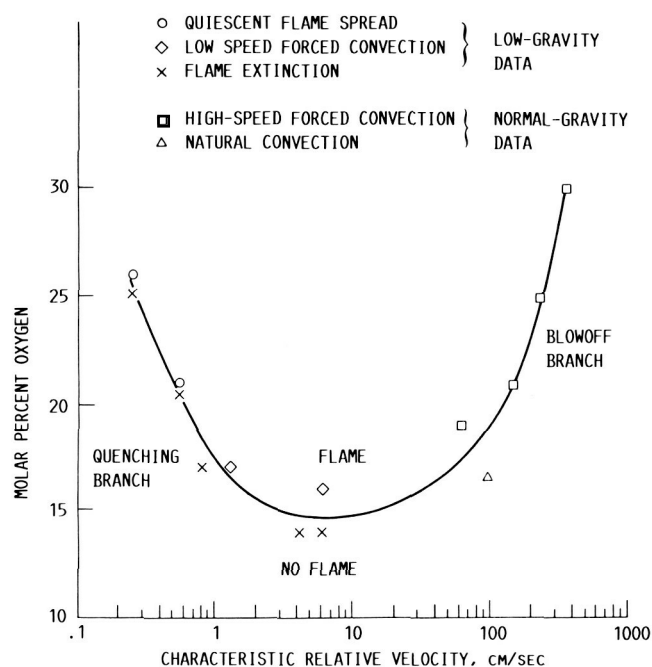


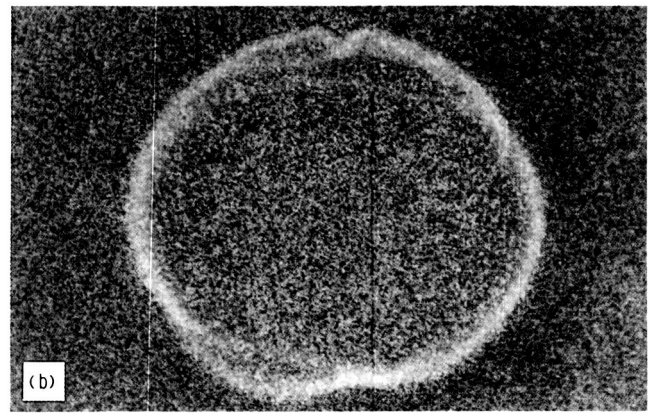
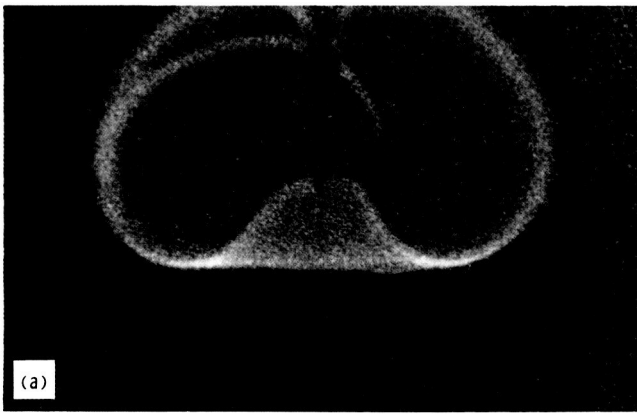
Figure 8.—Flammability map for paper as a function of environmental oxygen content and opposing flow velocity. (High-speed forced-convection data compiled in Fernandez-Pello et al., 18th Intern. Symp. on Combustion, 1981.)

within the flame zone. At low opposed flow velocities a quenching extinction is believed to be caused by excessive heat losses from surface radiation. Where the two extinction branches meet defines a minimum oxygen concentration for flammability. At oxygen concentrations lower than this minimum, the material will not burn regardless of the opposing flow velocity past the sample. This minimum oxygen concentration occurs at roughly the flow velocities that may be provided by a spacecraft's forced ventilation system.

Much is yet to be learned about the flammability of materials in low-gravity environments. Experiments such as smoldering combustion in low gravity are currently being defined for the shuttle and space station. The research results will assist in the selection of materials used in normal operations aboard spacecraft.

### Premixed Gas Combustion

Gravity affects premixed gas flames through buoyancy-driven convection. This effect is generally small except in mixtures with low burning velocities. In most fuel-air mixtures burning in normal gravity, this condition corresponds to mixture compositions far from stoichiometric. When the mixture is sufficiently fuel-lean or fuel-rich, buoyancy effects become apparent, as displayed in figures 9 and 10. In microgravity, flames ignited by a spark in the center of a constant-volume pressure vessel propagate in a slow, spherical fashion due to the reduction of buoyancy.



(a) In normal gravity the flame has a hemispherical shape due to buoyancy.

(b) In low gravity the flame shape is spherical. The small deformations are due to heat loss to the spark electrodes used for ignition.

Figure 9.—Effect of gravity on premixed gas flames. In each photograph a spark has ignited a pressure vessel (roughly 25,000 cm<sup>3</sup> in size) filled with 5.50 percent methane and air. Initial temperature and pressure, 23 °C and 1 atm. Photographed 0.25 sec after ignition.

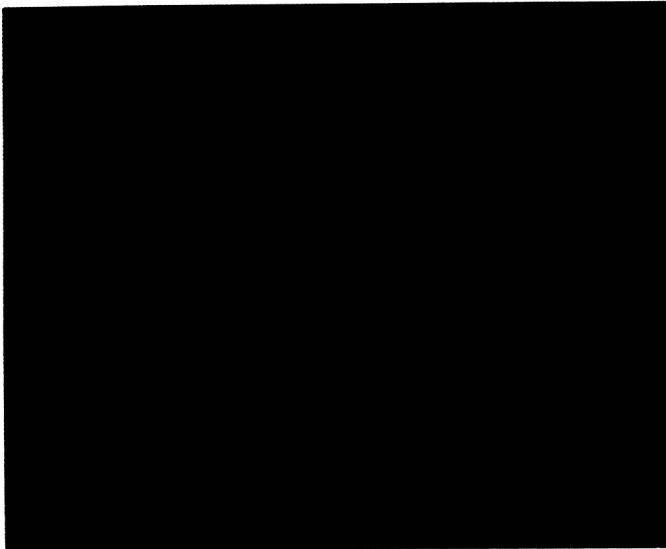


Figure 10.—Effect of low Lewis number on premixed gas flames. The flame splits into cells, each of which splits again. The cells form when a thermo-diffusive instability exists, i.e., when the premixed field of unburnt gas becomes nonuniformly enriched in hydrogen.

The limiting mixture compositions (e.g., most fuel-lean, most fuel-rich, or most dilute) that can sustain flame propagation are called flammability limits. Despite decades of study, the mechanisms of flammability limits are not well understood. Previous investigations in normal gravity suggested buoyant convection as the dominant contributor to these mechanisms. Recent microgravity studies, both theoretical and experimental, verified this suggestion, finding, *inter alia*, wider limits in microgravity than in the upward propagating flames of normal gravity. Furthermore, the properties of these limits were very different from those

observed in normal gravity. As opposed to buoyancy causing limits in normal gravity, radiative heat losses from the hot combustion gases are often the primary factor leading to flame extinguishment in microgravity.

A new mode of unstable flame propagation, called self-extinguishing flames, or SEF's, was observed for some mixtures whose compositions were outside the flammability limits. An SEF propagated a substantial distance from the ignition point but extinguished before nearing the walls of the pressure vessel. As opposed to a simple, failed ignition, the energy release before extinguishment was orders of magnitude larger than the ignition source energy. SEF's have only been observed in microgravity and for mixtures whose Lewis number<sup>1</sup> (*Le*) was less than 1. They are believed to result from the interaction of flame front curvature, unequal rates of diffusion of thermal energy and reactants (when  $Le \neq 1$ ), and radiant heat losses.

For mixtures with sufficiently low *Le*, propagating but discontinuous cellular flame structures have been observed. Several mechanisms have been identified that could lead to the formation of cellular structures. These include preferential diffusion of one reactant, diffusional-thermal instability, hydrodynamic instability, heat loss, and buoyancy. The interactions of these different mechanisms determine the conditions at which the cellular structure appear. Experiments (fig. 10), along with theory, suggest that diffusional-thermal instability was the dominant mechanism for cellular structure in microgravity.

<sup>1</sup>The Lewis number is defined as the ratio of the thermal diffusivity of the bulk mixture to the mass diffusivity of the stoichiometrically deficient reactant.

These premixed gas experiments involved flames propagating inside pressure vessels. Other experiments, with porous plate burners, have allowed the investigation of stationary flames. Preliminary results indicate that buoyancy is destabilizing instead of stabilizing.

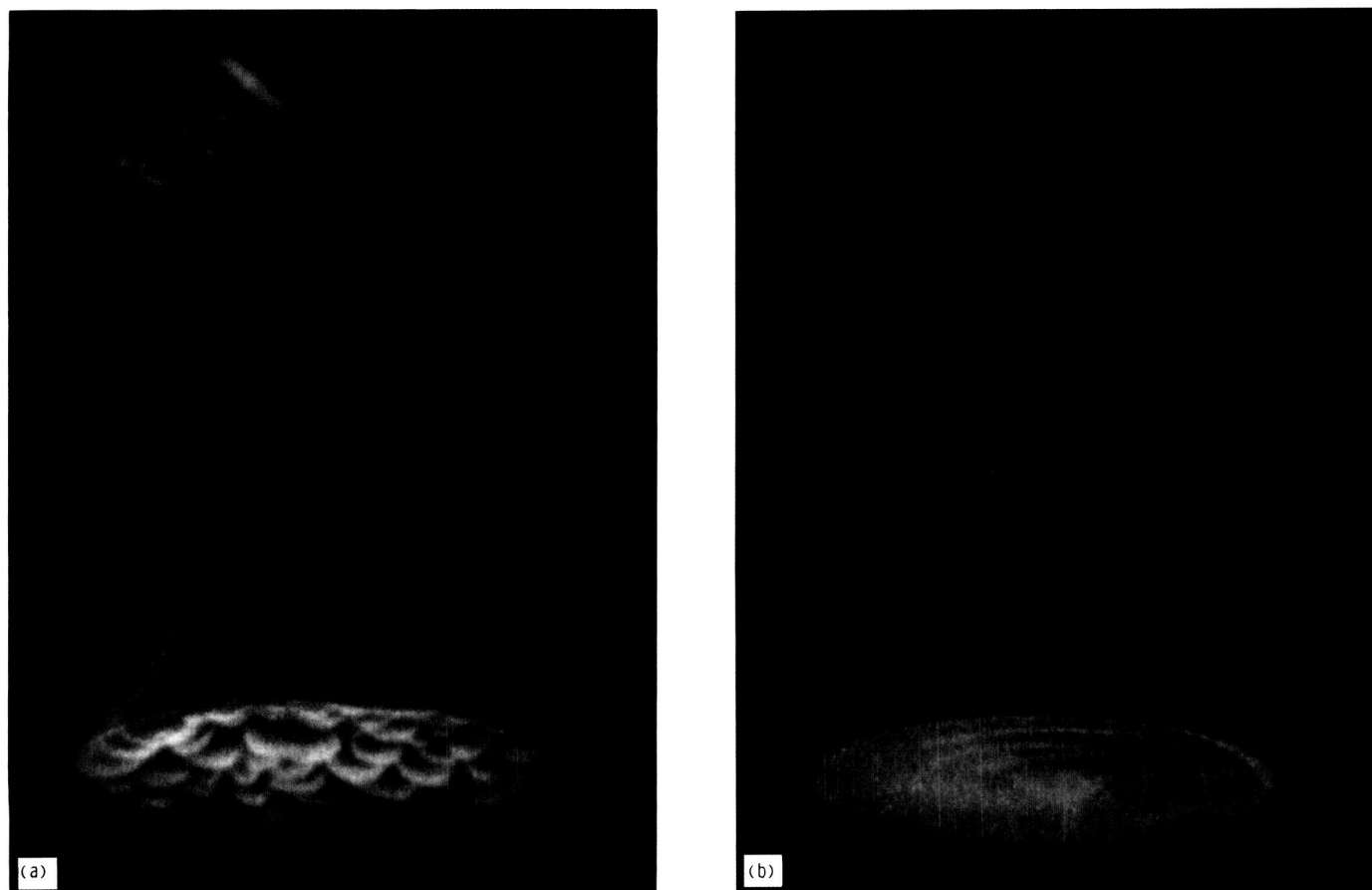
It was expected that the influence of buoyancy (with the hot combustion products over the cold reactants) would be responsible for overcoming the diffusional-thermal and hydrodynamic instability mechanisms, allowing more stable, planar flames to be achieved in normal gravity. Figure 11(a) shows a cellular flame, surrounded by an outer diffusion flame, in normal gravity prior to a drop tower test. Figure 11(b) shows the same flame, about 1.5 sec into the drop. The cellular structure is no longer apparent, although the flame is not flat. In the drop tower test, ripples, or pulsations, traveled radially outward along the flame front at approximately 9 Hz. Between pulsations, the flame became flat for about 30 msec. If buoyancy were stabilizing, the microgravity flame would be less stable and more distorted than its normal gravity counterpart.

Tests with porous plate burners are being continued in the 2.2-Second Drop Tower in a new test rig specifically built for cellular flame experiments. The effects of equivalence ratio, flow rate, and ambient pressure are being investigated. An improved understanding of the combustion instability mechanisms should result from these experiments.

Current experimental efforts in pressure vessels are investigating flames in a variety of fuels and oxidants in diluent gases having a wide range of diffusive and radiant transport properties. These tests will focus on quantitative verification of models of flammability limits, SEF's, cellular structures and flame bubbles in microgravity.

### Gas Jet Diffusion Flames

Gas jet diffusion flames embody mechanisms operating in both unwanted fires and controlled combustion systems. The flame structure is controlled by the interaction of these mechanisms (fig. 12). A better understanding of the simple laminar flame is a logical first step toward understanding the



(a) Normal gravity (before drop). Note cellular flame surrounded by a diffusion flame. (See fig. 22 for a better picture of the burner.)  
 (b) Low gravity (1.5 sec into drop). Note absence of cellular structure (image reversed).

Figure 11.—Porous plate burning experiment in 2.2-second drop tower. Reactants, propane in air; equivalence ratio, 1.40. The images in the top corner of the figure are mirror views.

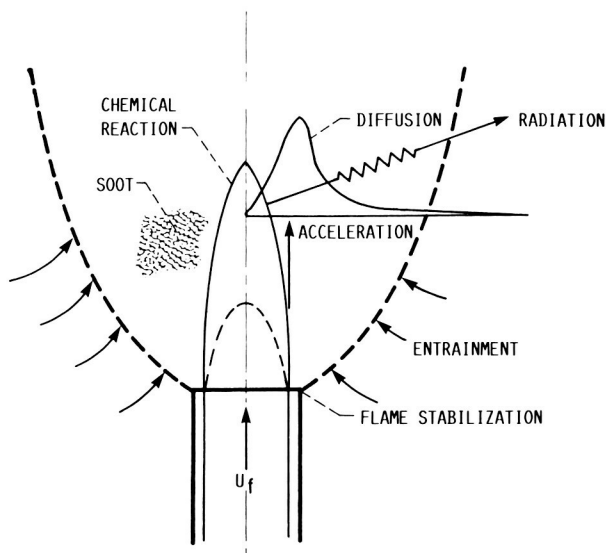


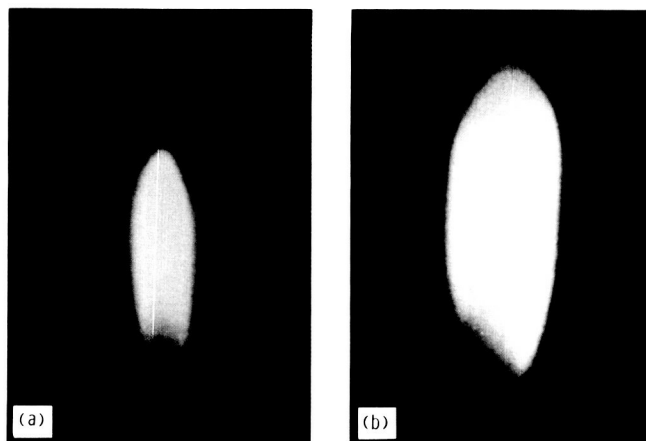
Figure 12.—Gas-jet diffusion flame structure. The steady-state structure of the laminar gas jet diffusion flame is a complex function of the mechanisms shown.

more complex turbulent diffusion flames that can be found in practical combustion systems, such as industrial burners. Another simplification can be made by studying the flames in a low-gravity environment. Isolating the effects of buoyancy significantly aids the analysis of the transport phenomena. A second benefit of studying the flames in low gravity is the acquisition of data that may aid in spacecraft fire safety.

Preliminary experiments with a fuel jet entering a quiescent environment are underway in the 2.2-Second Drop Tower in an effort to reveal the steady-state structure, ignition and flame development, soot generation and radiation, and flame quenching. As shown in figure 13 low-gravity flames are longer, wider, and often sootier than their normal-gravity counterparts. They are dimmer and more reddish, which indicates a lower flame temperature. Some appear to have open tips, which indicates local extinction (the identical normal-gravity flames have closed tips). The low-gravity flames exhibit little or no flickering. This result supports the hypothesis that the flicker is due to a hydrodynamic instability of the buoyancy-induced flow field.

Additional testing in the Zero Gravity Facility, where the longer times may allow the flame shape to reach steady state, will focus on the flame in a quiescent atmosphere (fig. 14). The combined effects of nozzle size, fuel, fuel flow rate, pressure, and oxygen concentration on the flame will be studied. Those flames that do not reach steady state in the test time will be studied using the KC-135 research aircraft.

A study of laminar Burke-Schumann diffusion flames is also beginning. These flames are enclosed gas jet diffusion flames with a coaxial flow of oxidizer and diluent surrounding the fuel jet. This experiment will provide additional information on the importance of the air flow and the inert diluent.



(a) Normal gravity.  
(b) Low gravity.

Figure 13.—The effect of gravity on a methane flame in quiescent air. The methane jet exits the 0.165-cm-i.d. tube at 3.0 cc/sec into the experiment chamber at 1.0 atm.

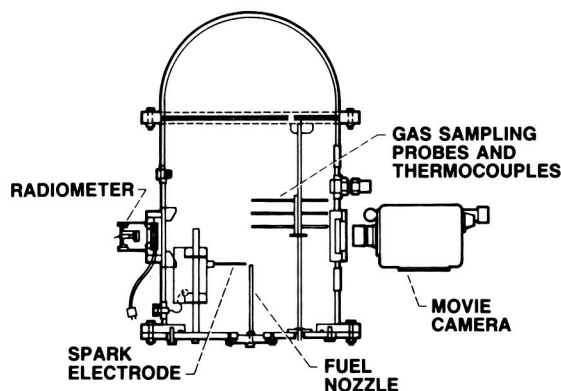


Figure 14.—Gas-jet diffusion flame study hardware for use in the zero gravity facility and the KC-135 research aircraft.

## Droplet Combustion

Understanding the basic physical mechanisms acting in the combustion of droplets, either alone or in arrays, is of long-standing scientific interest and of application to commercial combustion systems. The important scientific issues that can be studied without the masking influences of buoyancy are flame structure, burning rates, and the limits of flammability, as well as transport phenomena, particularly the role of thermophoretic forces.

Historically, the experiments with a single droplet under quiescent conditions in normal gravity have been limited to very small droplets suspended on fibers or falling in coflowing oxidizer streams. The microgravity environment allows much larger droplets to be studied, hence, more accurate visualization and probing of the combustion process can be attained.



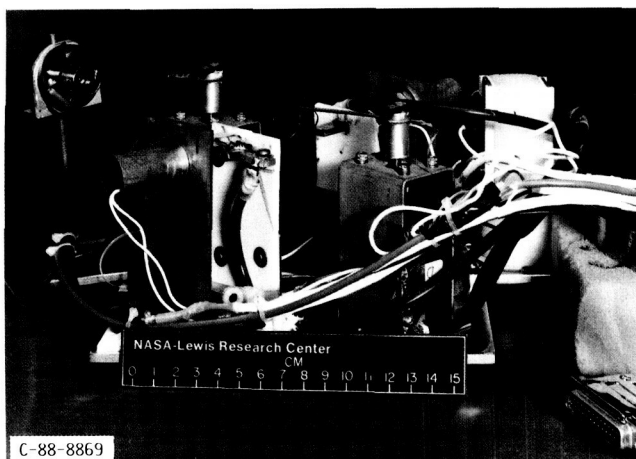


Figure 15.—Droplet combustion experiment apparatus. The experiment is performed in the Lewis 2.2-Second drop tower in the following steps: (1) The droplet, nominally 1 to 2 mm in diameter, is grown on two opposed needles. (2) The needles are slowly moved apart so the droplet is deformed near the point of separating from a needle. (3) In microgravity the droplet is deployed by simultaneous withdrawal of the needles. (4) Some 20 to 40  $\mu$ sec later, two parallel sparks, lasting several milliseconds, ignite the droplet. (5) After a several hundred millisecond heat induction period, the spherical flame appears around the droplet. The droplet velocity as well as the flame and droplet size are obtained by high-speed photography.

A microgravity droplet combustion experiment, which is currently being conducted in the Lewis drop towers, but which may require spaceflight, attempts to match more closely the assumptions of classical theory than is possible in normal-gravity experiments. The experimental apparatus is shown in figure 15. The apparatus allows single droplets to be deployed and ignited with postdeployment residual velocities as low as 2 mm/sec. While the experiment is focused on measuring the time-varying droplet and flame front sizes, disruption of decane/air droplets has been observed on some occasions (fig. 16). The disruption phenomena appears to be connected to the collapse of the soot shell surrounding the droplet onto the droplet itself. Local sites are rapidly heated, and subsequent rapid local vaporization causes the physical disruption of the droplet.

A theory is currently being developed to explain the quasi-steady location of the soot shell. The mechanism of instability of the soot shell is unknown. The soot shell interferes with the measurement of burning rates and extinction diameters. Near term studies focus on attempting to avoid this effect, so that complete combustion histories can be attained. Studies of other fuels, including heptane and methanol, are underway. The burning rates will be studied in varying oxidizer environ-

ments from 0.5 to 2 atm and oxygen mole concentrations below 50 percent.

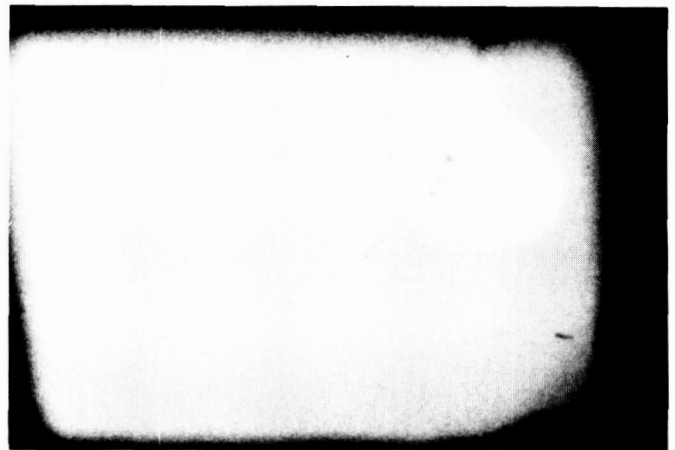
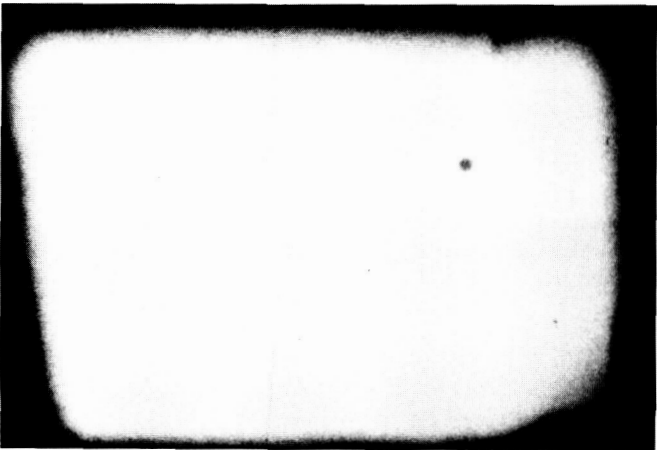
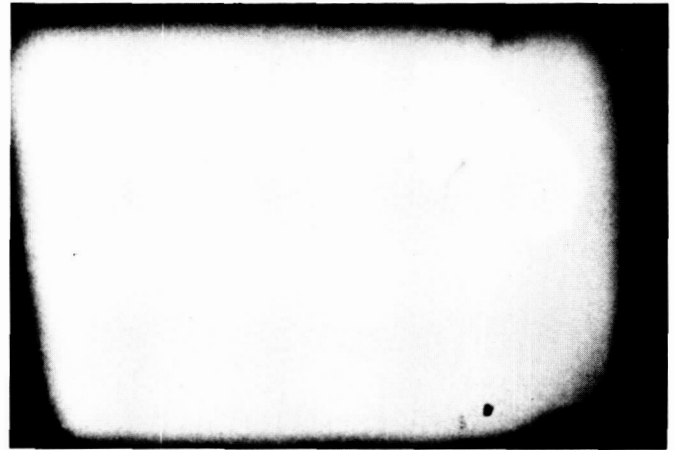
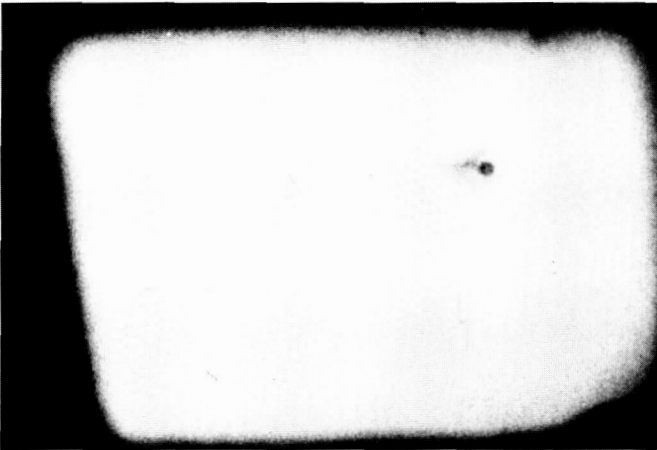
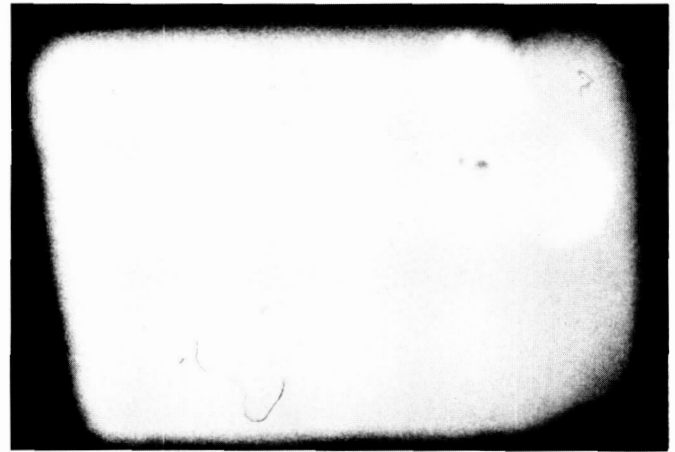
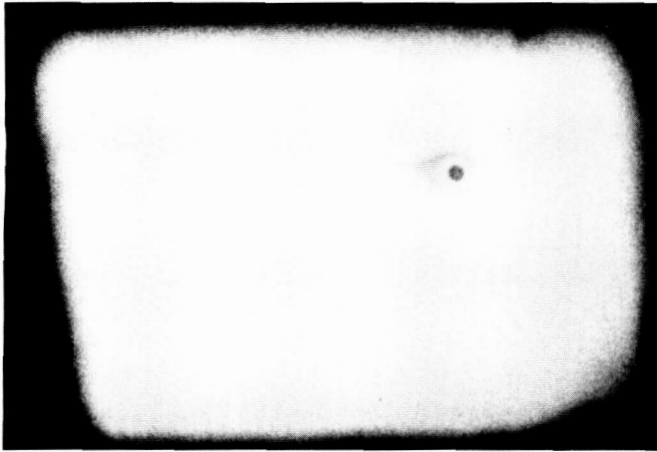
### Liquid Pool Fires

When a liquid pool of fuel is below its open cup flash point temperature, a heat source must provide energy to preheat and vaporize the fuel to a combustible composition for ignition to occur. After ignition the flame itself must provide the energy for preheat and vaporization for the flame to spread. In the presence of the heat source, liquid motion will be driven by both temperature-induced surface tension gradients and by liquid buoyancy. Gas phase motion is determined both by buoyant forces and the no-slip condition near the liquid-gas interface. Therefore, gravity affects the liquid- and gas-phase motions of the fuel and as such influences the supply of oxidizer and heat transfer ahead of the flame. The process is sufficiently complex that it is not clear, a priori, whether the ignition time and flame spread rate will be faster or slower in low gravity than in normal gravity. Two experiments are underway to make this determination.

In the first experiment liquid- and gas-phase motions are being studied before ignition in a small circular container heated nonuniformly from above (see fig. 17). Variations in container aspect ratio, liquid fill level, heater temperature and emissivity affect these motions. Initial studies in normal gravity have compared well with a new computational effort that captures the transient flow development. The studies have revealed that radiation, along with the heater temperature, determine to a large extent the number of observed cells. The computations predict that the flow patterns will be dramatically altered in low gravity. Drop tower experiments are underway to confirm this prediction, followed possibly by a space-based experiment.

In the second experiment, which will determine flame spread rates, 15-cm-diameter trays of quiescent alcohol fuels, at both subflash and superflash temperatures, are being ignited in the Lewis zero-gravity facility (see fig. 18). Both the pressure and oxygen concentration will be varied to determine their roles in the flame spread process. The data obtained will be used to verify a computational effort which predicts both the ignition delay time and the flame spread rate.

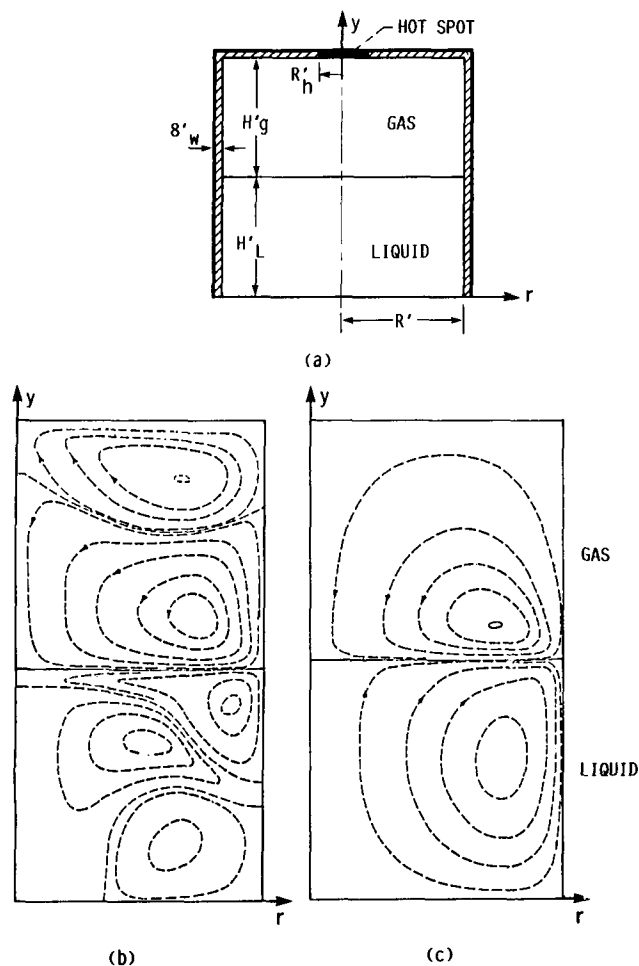
Both experiments are made difficult by the fact that the liquid surface tends to change from a "flat" configuration in normal gravity to one of constant curvature, related to its contact angle, in low gravity. The transition causes undesirable liquid motion, which must be damped out before ignition in order to allow easy interpretation of the experiment. Low-gravity experiments have shown that the damping time may be minimized by filling completely the tray and by reducing the tray's depth and diameter.



- (a) Starting position of fuel droplet with its surrounding soot shell.  
(b) The soot shell, through some instability mechanism, touches the droplet surface.  
(c) The droplet becomes darkened; the surrounding soot is missing.  
(d) The droplet rapidly expands in the direction of view.  
(e) The droplet contracts in the direction of view.  
(f) The droplet has spontaneously separated into three smaller droplets.

Figure 16.—Events leading to disruption of decane and air droplet in low gravity.





- (a) Geometry of the problem.
- (b) Predicted, normal-gravity flow streamline patterns. The flow was assumed to be axisymmetric and to result from buoyancy and thermocapillary forces. Thermal radiation from the heater to the side walls of the cylinder has a dramatic effect on the predicted flow pattern and the time to ignition. Flow visualization experiments are being conducted using flow tracers and a light sheet passing through the axis of the cylinder. Results to date show qualitative agreement with prediction.
- (c) Predicted, low-gravity flow streamline patterns. The effect of gravity is seen by comparing this flow pattern with that in part (b).

Figure 17.—Liquid pool preignition study. A 10-cm-diameter, 10-cm-high circular cylinder, filled with air or a liquid-gas mixture, is subjected to a sudden change in temperature in the center of its top surface.

## Particle Cloud Combustion

The study of combustible particle clouds is of fundamental scientific interest as well as a practical concern. Such clouds serve to spread fires in underground mining operations and contribute to the fire and explosion hazards in grain storage and handling facilities. Analogous to premixed gas combustion, of principal scientific interest are the characteristic

combustion properties, especially flame structure, propagation rates, stability limits, and the effects of stoichiometry, transport phenomena, and nonadiabatic processes.

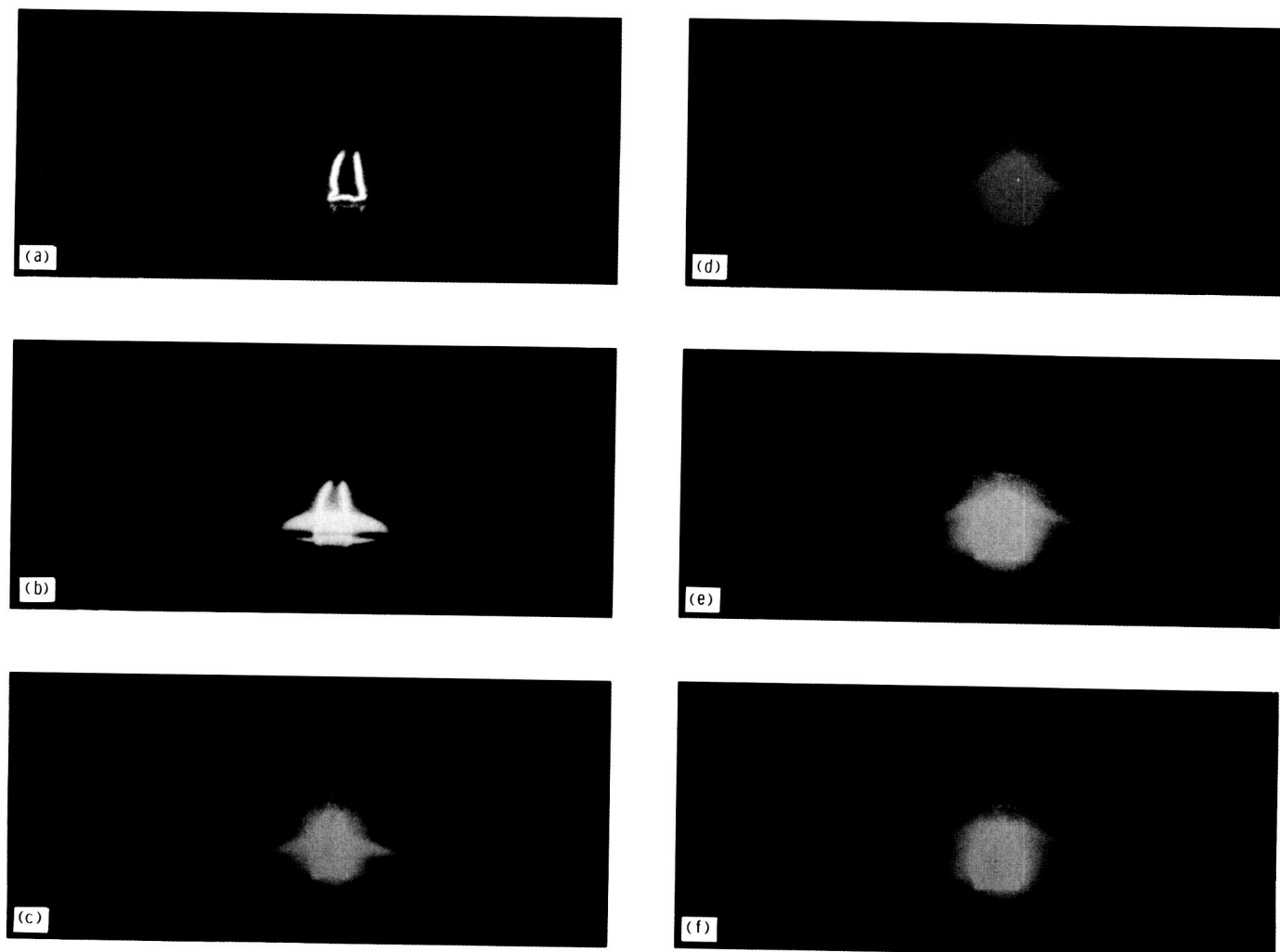
The experimental study of quiescent, uniform particle clouds has not been accomplished in normal gravity because of particle settling. To achieve uniformity, stirring devices or particle feeders, which sacrifice quiescence and introduce a time-dependent turbulent field, have been used. Such flow fields affect flame propagation and limit behavior. Further, the buoyantly driven flows induced by the spreading flame interact with the turbulent field in a manner beyond the current state of understanding.

As an alternative to normal-gravity experiments, a low-gravity experiment has been performed recently that emulates the characteristics of classical premixed gas studies and minimizes particle settling and buoyantly driven flows. Figure 19 describes the experiment (originally planned for spacecraft but now being conducted in aircraft), in which a flame propagates through a particle cloud suspended inside a standard diameter flame tube. A cloud uniformity on the order of  $\pm 10$  percent of the mean concentration was achieved. For fuel-rich mixtures quasi-steady flame propagation was observed. The shape of the flame front and wake structures were as anticipated but not previously obtained (see fig. 20(a)). Of greatest scientific interest is the finding that for near-stoichiometric mixtures a new mode of flame propagation was observed, now described as a "chattering flame" (see fig. 20(b)). These flames did not propagate steadily through the tube, but, instead, induced an acoustic disturbance (Kundt's tube) that segregated the suspended particles into alternating fuel-rich and fuel-lean laminae. The flame then propagated in a leaping, or chattering, fashion from one fuel-rich lamina to the next. A newly developed theory suggests that radiation from combustion products heats the successive fuel-rich laminae sufficiently to cause autoignition.

Chattering modes of flame propagation are not expected to display the same extinction limits as those for acoustically undisturbed, uniform quiescent clouds. Thus, the next step is to study fuel-lean concentrations to determine if and how they might support flame propagation. Then the effects of combinations of inert particles, premixed gases, fuel particle types, and tube geometries will be studied to develop a more complete understanding of the particle cloud combustion process.

## Spacecraft Fire Safety

Information about fire safety for practical low-gravity systems, (i.e., operational spacecraft) is an important byproduct of combustion research. A more complete understanding of combustion phenomena leads to flammability and fire-spread information for material screening and fire-prevention practices. An even more important research application comes from the investigation of low-gravity flame characteristics, an essential prerequisite for effective fire detection, extinguish-



(a) Time = 0 (hot-wire igniter energized).  
 (b) Time = 0.04 sec.  
 (c) Time = 0.12 sec.

(d) Time = 0.20 sec.  
 (e) Time = 0.28 sec.  
 (f) Time = 0.36 sec.

Figure 18.—Low-gravity flame spread study. Successive frames show side views of the flame spread across the surface of a 15-cm-diameter, 1-mm-deep pool of propanol at standard atmospheric conditions during microgravity. A similar top view showed the flame spread to be axisymmetric. The yellow and red plume in the center is due to the film's overexposure of the igniter and is not representative of the flame.

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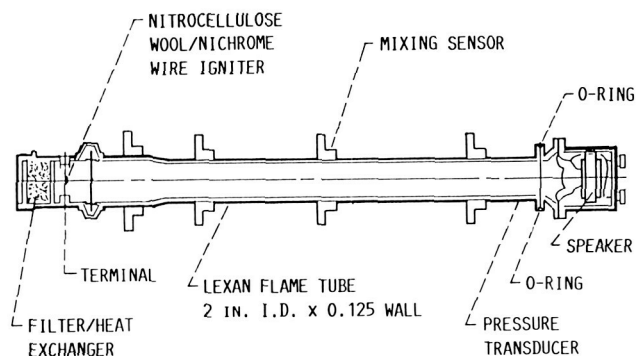
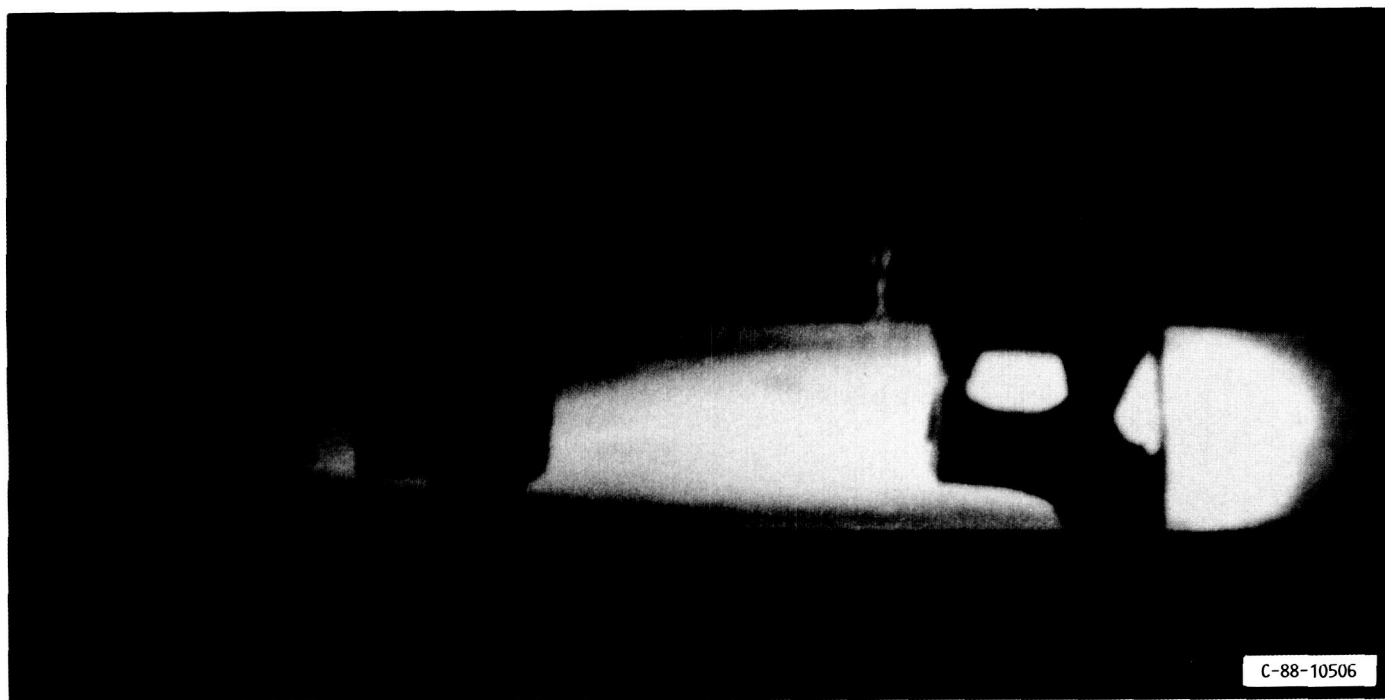
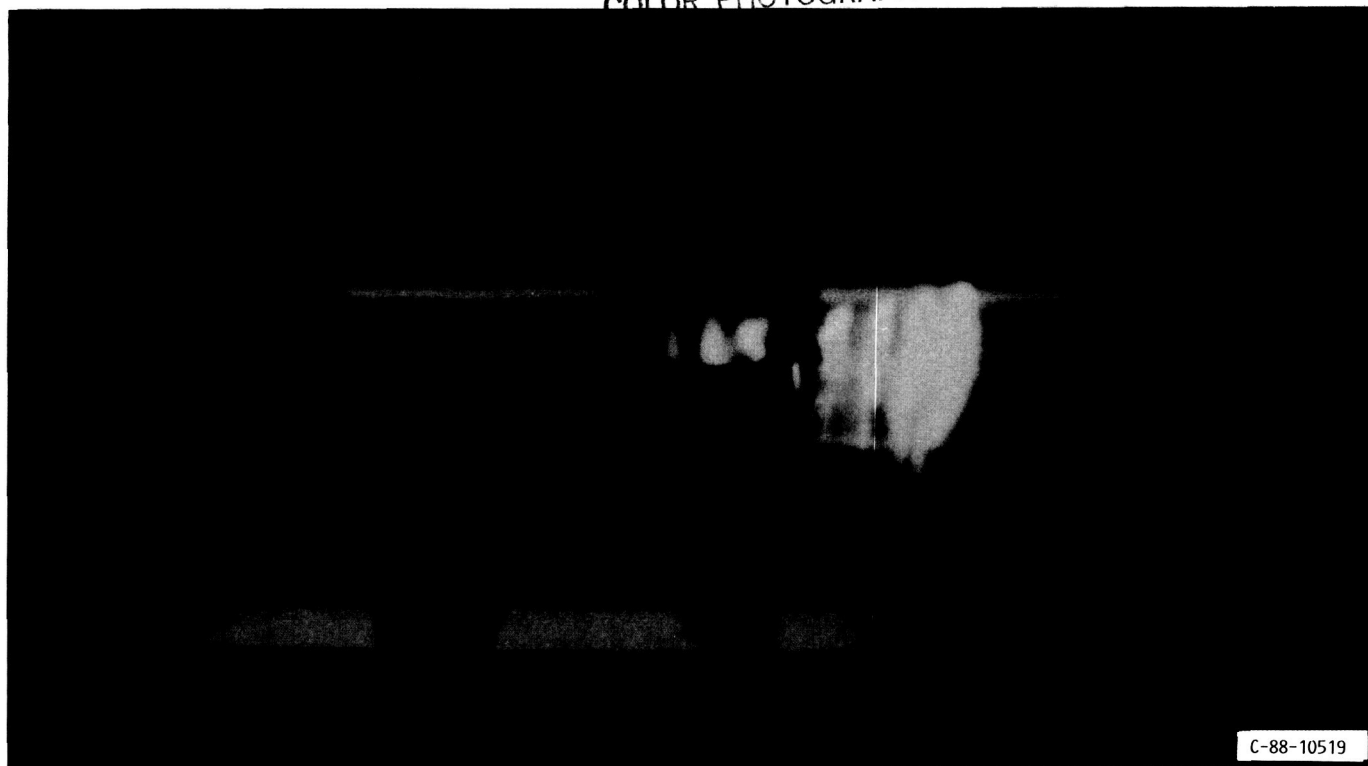


Figure 19.—Flame tube assembly for particle cloud combustion experiment. The tests were performed on the Lewis Learjet in the following stages: (1) lycopodium fuel particles ( $30\text{-}\mu\text{m}$  spheres) were mixed into cloud form by 0.5-sec sound burst from the loud speaker; (2) particle motion was allowed to decay toward quiescence during a 7- to 10-sec waiting period; (3) an igniter was energized which both opened one end of the tube and ignited the particle cloud; and (4) the flame proceeded down the tube length, with its position and shape photographed by high-speed cameras. Four optical sensors determined cloud uniformity and flame position.



(a) The long, continuous, symmetric tail is characteristic of lycopodium fuel-rich flames (here, with an equivalence ratio of 2.2). Had this experiment been performed in normal gravity, the flame front and tail would have bent upwards due to buoyancy. The observed flame speed (not the fundamental burning velocity) was about 40 cm/sec.

Figure 20.—Fuel-rich and near-stoichiometric flames photographed during particle cloud combustion experiment.



(b) The luminous tail of the near-stoichiometric, chattering flame is discontinuous and shorter than the flame in part (a). Chattering flames propagate more slowly and less steadily through the tube, on the order of 20 cm/sec.

Figure 20.—Concluded.

ment, and atmospheric rehabilitation in space. Low-gravity combustion research is also necessary in assessing the hazards of certain fire situations, smoldering, for example, that are profoundly affected by the reduction of the gravitational-field influence.

Application of combustion research to fire safety must also offer potential solutions to the demands for improved practices in the next generation of spacecraft. Long-duration and complex missions will increase the probability of the occurrence of fires and complicate the reduction of these hazards and their aftereffects.

Peripheral to combustion research but fundamental to fire safety programs are the decisions on risk analyses. The proposed space laboratories and workshops will certainly introduce materials, processes, and activities that are hazardous and have no effective substitutes. Risk optimization will involve trade-offs of acceptable risks balanced by resulting usefulness, efficiency, and cost effectiveness in space missions.

A variety of projects managed by the NASA Lewis Research Center are related to the needs of spacecraft fire safety. First, studies are in progress to analyze solid- and gas-phase reactions associated with cellulosic material burning and to measure low-gravity flammability at low levels of forced ventilation. Second, design definition is underway for in-flight experiment packages for fire-safety testing in multipurpose combustion chambers, to focus on inert atmospheres, smoldering, and fire extinguishment. Finally, planning and evaluation studies are

investigating fire standards, expert system risk analyses, and experimental project priorities for fire-safety research.

The accompanying list briefly describes some of the opportunities for research in combustion and outside fields of critical importance to spacecraft fire safety.

- Expansion of present analyses and research in fundamentals of low-gravity combustion.
- Development and evaluation of acceptance tests for non-flammable materials under low gravity
- Investigation of hazards from flammable aerosols in space (spills, etc.)
- Investigation of characteristics of signatures for fire detection in space
- Development of spacecraft fire-detection techniques and systems
- Development of spacecraft fire-extinguishment techniques
- Application of artificial intelligence and automation to guide fire-detection responses
- Development of environmental controls for postfire cleanup of spacecraft atmospheres

## Combustion Diagnostics Development

Advances in the understanding of microgravity combustion processes have been accompanied by a demand for diagnostic systems of greater sophistication. Influenced predominantly

by the harsh operational constraints imposed upon drop tower, aircraft, and spaceflight hardware, diagnostic apparatus to date has been relatively primitive, and predominantly qualitative in nature. Photographic recording and conventional transducers have provided the majority of low-gravity data.

A new program has been initiated for the development of measurement systems that are compatible with the various low-gravity research facilities. The specific aim of the Microgravity Fluids and Combustion Diagnostics Advanced Technology Development (MFCD/ATD) program is to pursue those technological refinements that are required to apply existing measurement techniques and to spawn the development of new techniques. In the absence of the relatively strong force of natural convection, microgravity combustion phenomena are generally more fragile and more easily perturbed than their normal-gravity counterparts. Hence, the primary emphasis has been placed on nonintrusive optical diagnostic techniques. Recent and continuing advances in the areas of integrated and fiber-optic technologies, solid-state optoelectronic materials and devices, and microelectronic device architectures will play a significant role in the evolution of these diagnostic systems.

Although the specific constraints imposed in the operation of the different low-gravity facilities vary to some degree (such as the large decelerations at the conclusion of drop tower experiments and the rigorous safety and design reviews levied upon spaceflight hardware), many design goals are common to all of them. Low power consumption, low volume and weight limitations, simplicity, reliable and safe operation, and tolerance to mechanical vibration are significant design considerations. Most techniques currently used in terrestrial laboratories are unsuitable for in-space use because of, for example, high power consumption, size, system complexity, or maintenance requirements.

The specific measurement parameters most generally of

interest have been categorized into one of four areas: (1) flow visualization and qualitative imaging, (2) temperature and species concentration fields, (3) velocity fields, and (4) particle size distributions and concentrations. Multipoint or multi-dimensional diagnostic techniques are currently favored. This is clearly not feasible in all cases, however, because of such factors as optical source strength requirements, as is presently the situation with planar laser-induced fluorescence techniques. The additional requirements for overall operational reliability and autonomy have tended to promote less frequently emphasized and simpler techniques such as refractive index mapping and molecular Rayleigh scattering, as shown in figures 21 and 22.

## Space Station Freedom's Combustion Facility

The prospect of a permanently inhabited, orbiting laboratory is about to be realized with the development efforts to construct Space Station Freedom. Research will be performed in a laboratory specifically designed for microgravity experiments. To fully utilize this capability, a facility will be developed to accommodate multiple combustion experiments.

As shown in figure 23, the Modular Combustion Facility (MCF) is conceived as a highly modular system with a facility rack—for instrumentation hardware commonly needed by many experiments—and an experiment rack for experiment-specific apparatus. The use of commonly needed equipment in the facility rack avoids the high cost of repeatedly developing flight-qualified hardware. The flexibility required to perform diverse experiments will be maintained by the capability of the experiment rack to permit changeout and reconfiguration of apparatus and diagnostic instrumentation.

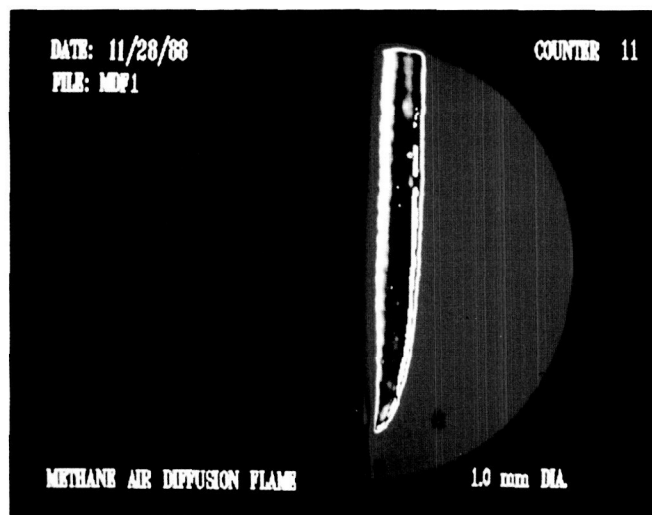


Figure 21.—A false colored schlieren image of a methane-air diffusion flame in normal gravity. Qualitative flow visualization is useful for identifying the inherent length and time scales under study, as well as for providing insight into the dynamics of mixing and transport processes.

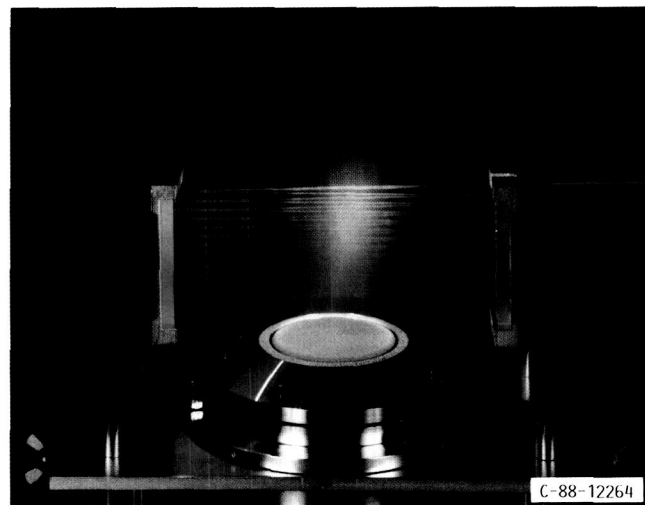


Figure 22.—A sheet of laser light formed by a confocal, multipass cavity. Rayleigh scattered photons will be imaged to two-dimensional gas-phase densities of this methane-air flame above a porous plate burner in normal gravity.

The cost saving of multiuser subsystems is obvious; however, the specification of design parameters for flight hardware that must be compatible with experiments several years from conception is not practical. The evolutionary approach to the facility design will provide the opportunity to simultaneously nurture the science of microgravity combustion and the technology of space-based combustion experiments. Simple experiment payloads, dedicated to the requirements of a single investigator, are to be followed by more advanced payloads that accommodate several. Finally, with the experience of accommodating multiple users, facility-class hardware will be developed that provides an optimum mixture of cost-effective, multiuser hardware and high quality science return for a wide spectrum of combustion experiments.

The mileposts of the MCF development are the several Spacelab missions that are planned through the initial operations of the Space Station Freedom in the late 1990's. Current flight manifests include two single-user combustion payloads, the Solid Surface Combustion Experiment and the Droplet Combustion Experiment, to be flown on the USML-1 mission in 1992. Although the observations of the astronauts performing the experiments are an important part of the experimental results, the experiment operations are semi-automatic and self-contained.

Studies are now being performed to identify a multiuser payload for the USML-2 mission in 1993. Because of the multiuser nature of this new payload, a capability to vent combustion products overboard and changout fuel and oxidizer supplies will be required. Thus exposure of the combustion chamber interior to the cabin environment is required for the first time and represents a significant safety challenge to the

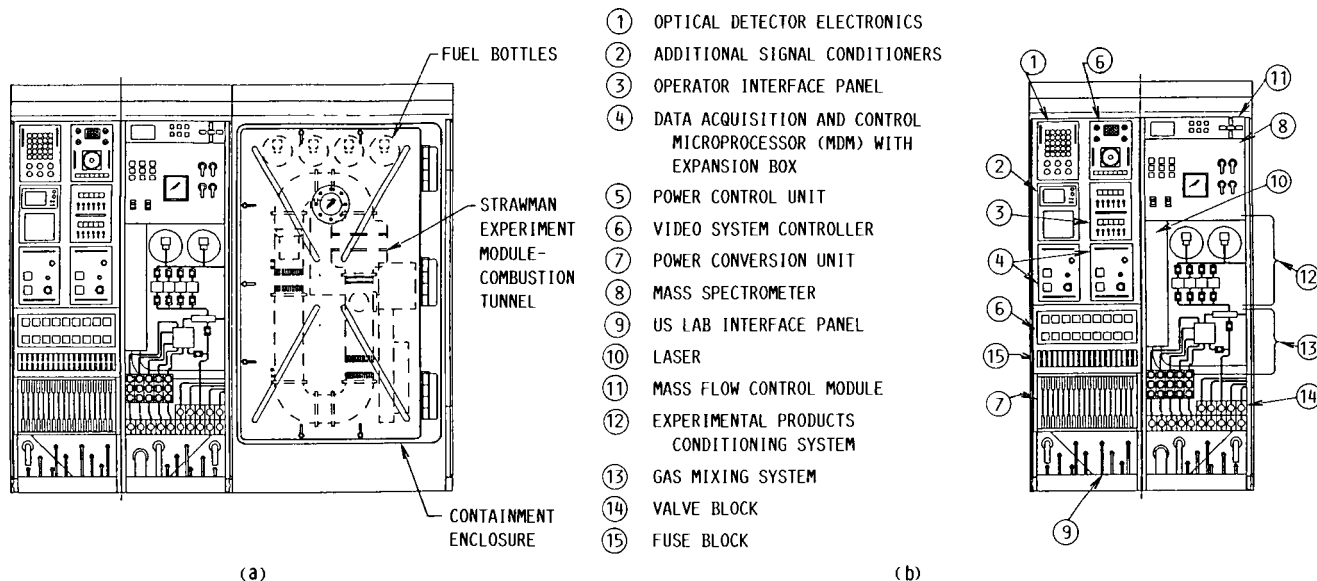
payload designers. The feasibility of including remote sensing diagnostic methods with this payload for gas-phase velocities, temperatures, or composition measurements is being evaluated. It may be necessary to reconfigure various diagnostic components for the different users while in flight, so the need for astronaut involvement in experiment operations will expand with multiuser payloads. Following the USML-2 mission, a complement of up to three multiuser payloads may be part of the MCF development.

In the era of Space Station Freedom operations, facility-class hardware will, with the aid of high-fidelity communications between the investigators on Earth and the astronaut-scientist, accommodate the key experiments specified by the investigator before the mission, and allow the nearly real-time investigation of unanticipated findings. Within a 90-day mission, extensive apparatus and diagnostic changeout or reconfiguration will be possible so that a highly productive combustion laboratory will be available to serve the needs of a diverse scientific community.

## Program Participation

NASA provides financial and facility support, typically for a three year "definition study" period, to academic and industrial principal investigators. Their initial proposals and subsequent progress are evaluated via the peer review process which addresses the following types of questions:

- Is there a clear need for microgravity experimentation, particularly space-based experimentation?



(a) The facility rack is shown (left) next to a rack dedicated to experiment-specific hardware, in this case, a low-speed combustion tunnel.

(b) The layout of common equipment to be located on the facility rack is shown. These items have been specified to allow many different types of combustion experiments.

Figure 23.—The modular combustion facility for Space Station Freedom consists of two double racks in the U.S. laboratory module.

- Is the effort likely to result in a significant advance to the state of understanding?
- Is the scientific problem being examined of sufficient intrinsic interest or practical application?
- Is the conceptual design and technology required to conduct the experiment sufficiently developed to ensure a high probability of success?

Principal investigators collaborate with a NASA technical monitor to conduct the necessary research to answer these questions. Work in the drop towers and aircraft is strongly encouraged during this definition study period.

If it is believed that spaceflight experiments are needed, the principal investigators then present their results to a NASA-sponsored review panel composed of their scientific and engineering peers. If the review is successful, NASA assigns a team of engineers and scientists to the multiyear development of spaceflight hardware that meets the principal investigators' specifications. NASA continues project support by conducting additional research, consulting with the principal investigators, and providing design and safety reviews before spaceflight. The principal investigator then monitors the experiment in flight and subsequently analyzes and publishes the data.

The above scenario is typical for space-based experiments; however, NASA also supports theoretical research and microgravity experiments that can be completed in the drop towers or aircraft.

More information about the details of the process of proposal submission, progress reviews, and spaceflight project selection is available by writing to the Microgravity Combustion Group, MS 500-217, Lewis Research Center, NASA, 21000 Brookpark Road, Cleveland, Ohio 44135.

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16. Abstract  <p>The purpose of this document is to provide an introduction to the promise of microgravity combustion research by way of a brief survey of results, the available set of reduced gravity facilities, and plans for experimental capabilities in the Space Station era. The study of fundamental combustion processes in a microgravity environment is a relatively new scientific endeavor. A few simple, precursor experiments were conducted in the early 1970's. Today the advent of the U.S. space shuttle and the anticipation of the Space Station Freedom provide for scientists and engineers a special opportunity—in the form of long duration microgravity laboratories—and need—in the form of spacecraft fire safety and a variety of terrestrial applications—to pursue fresh insight into the basic physics of combustion. The microgravity environment enables a new range of experiments to be performed since buoyancy-induced flows are nearly eliminated, normally obscured forces and flows may be isolated, gravitational settling or sedimentation is nearly eliminated, and larger time or length scales in experiments become permissible. The range of experiments completed to date has not been broad, but is growing. Unexpected phenomena have been observed often in microgravity combustion experiments, raising questions about the degree of accuracy and completion of our classical understanding and our ability to estimate spacecraft fire hazards. Because of the field's relative immaturity, instrumentation has been restricted primarily to high-speed photography. To better explain these findings, more sophisticated diagnostic instrumentation—similar to that evolving in terrestrial laboratories—is being developed for use on Space Station Freedom and, along the way, in existing microgravity facilities.</p>					
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